Anthropogenic and natural sources of ionizing radiation: environmental distribution, human exposure pathways, and radiobiological implications

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Abstract. Ionizing radiation represents a ubiquitous environmental factor originating from both natural and anthropogenic sources. This study provides an integrated assessment of the major contributors to human radiation exposure, including terrestrial radionuclides, cosmic radiation, medical diagnostic procedures, nuclear industry activities, and fallout from nuclear accidents and weapons testing. Particular attention is given to key radionuclides such as cesium-137, strontium-90, iodine-131, uranium, and thorium, emphasizing their half-lives, environmental persistence, and biological uptake mechanisms. The analysis explores the distribution of radionuclides across environmental compartments and their transfer through food chains, leading to internal exposure in humans and biota. Dose assessment data are synthesized to compare the relative contributions of different radiation sources to the total annual effective dose. Furthermore, the study reviews radiobiological effects associated with chronic low-dose exposure, highlighting uncertainties in risk estimation. The findings underscore the dominant role of medical exposures among anthropogenic sources and the long-term environmental impact of radionuclides released during nuclear incidents. This work contributes to a better understanding of radiation exposure dynamics and supports the development of improved radiological protection strategies.

Keywords: artificial radiation, medical imaging, nuclear power, radioactive contamination, Chernobyl, Fukushima.

Introduction. Radiation represents a form of energy that propagates through space in the form of electromagnetic waves or particles. Artificial radiation is widely used throughout industry, primarily for process and product quality control, for diagnostic purposes in dentistry and veterinary medicine, and finally as an important means of study in colleges, universities, and others (Petrescu-Mag & Oroian, 2015). In addition to the radiation that naturally exists in the environment, humans have developed numerous artificial sources of radiation to meet the needs of modern society (Omer, 2021).

Artificial radiation is produced through human-made activities and technologies, such as X-ray machines, computed tomography (CT) scanners, nuclear power plants, industrial equipment, and various electronic devices. These sources have brought significant benefits, contributing to the diagnosis and treatment of diseases, industrial development, and scientific progress. However, the use of artificial radiation also involves certain risks to human health and the environment when appropriate safety measures are not followed. For this reason, it is essential to understand the sources of radiation, their effects, and the methods by which exposure can be controlled. This review presents the main types of artificial radiation, the fields in which they are used, their effects on the human body, and the protective measures necessary for their safe use.

Aim of the Study. The present study aims to systematically evaluate the principal natural and anthropogenic sources of ionizing radiation, with a particular focus on their environmental dispersion, radiological characteristics, and contribution to human exposure. The work further seeks to analyze the behavior of key radionuclides in environmental compartments (soil, water, and air), their bioaccumulation potential, and the associated biological effects on living organisms. Additionally, the study addresses the relative significance of medical, industrial, and accidental radiation sources in shaping overall population dose burdens.

General Information about Radiation. In physics, 'radiation' refers to the transfer of energy from a source outward in the form of waves or particles that propagate through space or through a material medium. This energy can sometimes be harmful, at other times beneficial, or even essential to life. Radiation is the emission or transmission of energy in the form of waves or particles, through space or through a material medium, capable of penetrating various materials (Ahmed, 2014; Cerrito, 2017; Kanagasabay, 1982; Karmaker et al., 2021; Katsumura & Kudo, 2018; L'annunziata, 2020; Susmitha, 2025; Venkateshan, 2021). Extent of radiation exposure to inhabitants in different parts of the world varies depending on the occurrences of the radioactive geologic sources as well as on the availability of the beneficial nuclear facilities to the users (Das, 2018). The ionizing radiations such as X-rays, α, β, or γ – rays, at higher doses, are generally harmful to people. On average, the natural radiation exposure dose to humans is ~ 3 mSv per year (Das, 2018).

Radiation Exposure from Natural, Medical, and Technogenic Sources. Human exposure to ionizing radiation arises from natural background, medical uses, occupational sources, and nuclear accidents or tests. The studies below quantify typical effective doses in millisieverts per year (mSv/y) or per procedure and compare them with regulatory limits and historical fallout.

Types and levels of radiation exposure*.* Natural background radiation delivers around 2–2.4 mSv per year worldwide, with major contributions from radon and thoron progeny, internal radionuclides, and cosmic and terrestrial gamma radiation (Thorne, 2003; Sivintsev, 1957). Fallout from atmospheric nuclear weapons testing peaked at about 0.11 mSv/y (about 5% of natural background) in 1963 and has since declined to ~0.006 mSv/y (Thorne, 2003; Mettler et al., 2008; Gibson & Peirson, 1968).

Medical exposure in the United States increased dramatically between 1980 and 2006, reaching about 3 mSv/y per capita and approximately equaling natural background, mainly due to computed tomography and nuclear medicine (Mettler et al., 2020; Mahesh et al., 2022; Mettler et al., 2008; Einstein, 2020). By 2016, per capita medical dose had decreased to ~2.2–2.3 mSv/y, despite stable or slightly increased CT use, due to dose optimization and reduced nuclear medicine and fluoroscopic procedures (Mettler et al., 2020; Mahesh et al., 2022; Einstein, 2020). In Portugal, mean effective dose from x-ray diagnostics rose from 0.75 to 0.89 mSv per capita between 2013 and 2017, with CT as the dominant contributor, while nuclear medicine contributed about 0.09 mSv/y (Teles et al., 2020).

Occupationally, worldwide average annual effective dose for monitored workers is about 1.2 mSv, higher (≈2 mSv) for those exposed to natural sources and lower (≈0.5 mSv) for workers exposed mainly to artificial sources (Chen, 2023). In one Russian region, average annual individual occupational doses ranged from 0.66 to 2.02 mSv, well below regulatory limits of 20 mSv/y (Стёпкин et al., 2016; Chen, 2023).

Accidents, nuclear installations, and environmental fallout*.* After the Fukushima accident, external doses from artificial radionuclides in a Japanese town in 2020 produced median annual effective doses of 0.40 mSv in a re-opened zone and 3.9 mSv in a difficult-to-return zone, compared with 0.19–0.25 mSv from natural radionuclides (Ogura et al., 2021). Modeling of cesium-137 fallout indicates that areas near Chernobyl received annual external effective doses up to 10 times higher than comparable areas near Fukushima and that skin receives the largest organ dose (Wai et al., 2020). Scenario modeling of nuclear power plant fallout suggests 50-year cumulative effective doses between about 0.14 and 1.5 mSv per kBq/m² of 137Cs, highly dependent on mitigation measures such as relocation and food controls (Isaksson et al., 2019).

An impact study of a hypothetical severe AP1000 reactor accident estimated total effective doses of about 27 Sv at 0.6 km and 8 Sv at 2 km under different meteorological periods, far above public (1 mSv/y) and worker (20 mSv/y) annual limits and requiring urgent protective actions (Dadda et al., 2024). Historical analyses of French atmospheric nuclear tests in Polynesia indicate that earlier official estimates of annual effective doses to the public were underestimated by factors of 2–10, implying that roughly 110,000 people may have exceeded 1 mSv/y in some years, a threshold used for compensation eligibility (Philippe et al., 2021).

Medical and low-dose risk considerations*.* Systematic review of low-dose (below 200 mSv) x-ray and gamma exposures found that most of higher-quality epidemiological studies do not support increased cancer risk up to cumulative doses of about 100–200 mSv, although a minority do, and uncertainties remain (Schultz et al., 2020). In contrast, a review of CT-related radiation exposure reports increased risks of brain tumors, central nervous system tumors, leukemia, lymphoma, and other malignancies in children, particularly with repeated CT examinations or predisposing factors, though study representativeness and bias limit firm conclusions (Buchberger et al., 2022). A meta-analysis of occupational and environmental exposures around nuclear power plants reported elevated risks of all cancers, thyroid cancer, and leukemia among residents, especially children under five, and higher mesothelioma risk among workers, with some evidence of a dose–response for circulatory diseases in workers, but with incomplete control of confounders in many studies (Lin et al., 2024).

Large-scale dose assessments show that diagnostic and interventional medical procedures in the United States contributed about 2.2–2.3 mSv per capita in 2016, from approximately 691 million radiologic, CT, dental, and nuclear medicine studies, representing about 17.6% of the world’s collective medical dose, despite the United States performing only 16.5% of global procedures (Mettler et al., 2020; Mahesh et al., 2022). A Russian CT registry near a nuclear facility reports an average effective dose of about 4.7 mSv per CT examination and a cohort cancer prevalence of about 20%, providing a basis for future long-term risk estimation for diagnostic exposures in a mixed-exposure population (Osipov et al., 2025).

Concerns that medical x-ray use could confound atomic bomb survivor risk analyses appear limited: among survivors with doses below 1 Gy, frequency of CT, fluoroscopy, angiography, and radiotherapy did not vary meaningfully with bomb dose, and among those above 1 Gy, additional medical doses are small compared with the original exposure (Sadakane et al., 2019).

Comparative effective doses from major sources*.* Across the literature, natural background radiation provides a relatively stable baseline of about 2–2.4 mSv per year, while medical exposures in high-use countries can contribute comparable or greater doses, though recent trends in the United States show stabilization or decline due to optimization. Occupational doses under normal operation are generally below regulatory limits, but nuclear accidents and weapons tests can create localized or episodic exposures far exceeding typical background and regulatory thresholds. Evidence on cancer risk from low-dose diagnostic and environmental exposures is heterogeneous: methodologically stronger studies often find little or no excess risk up to cumulative doses around 100–200 mSv, yet elevated risks in specific groups, particularly children and residents near nuclear installations, underline the need for cautious use of ionizing radiation, robust dose monitoring, and long-term epidemiological follow-up (Table 1).

Table 1

Typical annual or per-event effective doses/ comparison of approximate effective doses from key radiation sources

Exposure source or scenario	*Typical effective dose (approximate)*	*Context / notes*	*References*
Natural background (world average)	2–2.4 mSv per year	Includes radon, internal and external radionuclides, cosmic rays	Thorne, 2003; Sivintsev, 1957
Global weapons fallout (peak 1963)	≈0.11 mSv per year	~5% of natural background at peak, now ~0.006 mSv/y	Thorne, 2003; Mettler et al., 2008; Gibson & Peirson, 1968
Medical procedures, U.S. 2006	≈2.9–3.0 mSv per capita per year	Dominated by CT and nuclear medicine	Mettler et al., 2020; Mettler et al., 2008; Einstein, 2020
Medical procedures, U.S. 2016	≈2.2–2.3 mSv per capita per year	Reduced collective dose despite population growth	Mettler et al., 2020; Mahesh et al., 2022; Einstein, 2020
X-ray diagnostics, Portugal 2017	≈0.89 mSv per capita per year	CT main contributor	Teles et al., 2020
Nuclear medicine, Portugal 2017	≈0.090 mSv per capita per year	Bone and cardiac exams dominate	Teles et al., 2020
Average occupational dose, global	≈1.2 mSv per year	≈2 mSv/y (natural sources); ≈0.5 mSv/y (artificial)	Chen, 2023
Occupational dose, Voronezh region	0.66–2.02 mSv per year	Under normal operation, below 20 mSv/y limit	Stepkin et al., 2016; Chen, 2023
External natural radionuclides, Namie town	≈0.19–0.25 mSv per year	Natural background in 2020	Ogura et al., 2021
External artificial radionuclides, Fukushima-impacted zones	≈0.40–3.9 mSv per year	Higher in difficult-to-return zone	Ogura et al., 2021; Wai et al., 2020
Severe hypothetical AP1000 accident (near field)	8–27 Sv (acute)	Much higher than annual limits; emergency conditions	Dadda et al., 2024
CT examination (Russian registry)	≈4.7 mSv per scan	Average effective dose per CT	Osipov et al., 2025; Mettler et al., 2020.

Key Anthropogenic Radionuclides and Their Behavior. This chapter summarizes available data from the papers on cesium-137, strontium-90, iodine-131, uranium and thorium: their half-lives, main environmental compartments, bioaccumulation and main target organs. For Sr-90 there are only indirect data; for some details on Th information is very limited (Table 2).

Cesium-137 has a physical half-life of about 30 years and is water-soluble, allowing it to travel efficiently in air and then contaminate soil, water and living organisms after atmospheric deposition. It is mobile and bioavailable in aquatic systems and is readily accumulated by microorganisms and aquatic plants and then recirculated for many years in food webs. It distributes fairly uniformly in soft tissues, so the whole body becomes a target organ for prolonged internal exposure (Zaletel et al., 2024; Ashraf et al., 2014; Okhrimchuk et al., 2024). Strontium-90 has a half-life of 28 years and behaves chemically like calcium, so after intake it preferentially accumulates in bones and teeth, making bone and bone marrow the main target organs. The papers describe this biokinetic behavior but give little detail on its environmental transport compared with cesium (Zaletel et al., 2024). Iodine-131 has a half-life of about 8 days and is water-soluble and volatile; during nuclear accidents it contaminates air, water, soil, vegetation and food, but because of its short half-life it does not cause long-term environmental contamination. It is efficiently taken up into the thyroid via the sodium-iodide symporter, where 10–30% of the incorporated amount can accumulate within 24 hours, making the thyroid the critical target organ and explaining its strong link with thyroid cancer risk (Zaletel et al., 2024; Schomäcker et al., 2026; Drozdovitch, 2021; Uchiyama et al., 2018; Latifah et al., 2024; Íbiş et al., 1992). Uranium is a long-lived radionuclide; specific isotopic half-lives are not detailed in these abstracts, but uranium is widespread in soil and aquatic environments due to mining, industry and waste. It can accumulate strongly in roots of plants and in aquatic organisms, and in humans it is retained mainly in kidneys, liver, bone and soft tissues, which are therefore the principal target organs for both chemical toxicity and radiological dose (Chen et al., 2021; Bangotra et al., 2021; Xu et al., 2021; Patel et al., 2023; Akash et al., 2022; Fallatah et al., 2024). Thorium isotopes are also long-lived, but the abstracts give no explicit numeric half-lives. Thorium can reach high concentrations in soils and sediments and occurs in air and water near extraction and use sites. Biota generally take up only small amounts, and specific target-organ distributions in humans are not well described in these summaries, although thorium behaves as a heavy metal and, when inhaled as dust, is associated with increased lung cancer risk (Rump et al., 2023; Patel et al., 2023).

Table 2

Key properties of major anthropogenic radionuclides:
comparison of half-life, compartments and targets

Radionuclide	*Approximate physical half-life (from papers)*	*Main environmental compartments emphasized*	*Bioaccumulation behavior described*	*Main target organ(s) in biota/humans*	*References*
Cs-137	~30 years	Air (transport), then soil, water, biota	High mobility and bioavailability; long-term recirculation in aquatic and forest ecosystems	Soft tissues of whole body (prolonged internal exposure)	Zaletel et al., 2024; Okhrimchuk et al., 2024; Ashraf et al., 2014; Drozdovitch, 2021
Sr-90	28 years	Not detailed, implied fallout to soil and food chains	Follows calcium behavior	Bone and bone marrow	Zaletel et al., 2024
I-131	8.0–8.02 days	Air, water, soil, vegetation, food, milk	Rapid thyroid uptake of 10–30% of intake; short environmental	Thyroid gland	Zaletel et al., 2024; Schomäcker et al., 2026;

Radionuclide	*Approximate physical half-life (from papers)*	*Main environmental compartments emphasized*	*Bioaccumulation behavior described*	*Main target organ(s) in biota/humans*	*References*
			persistence		Drozdovitch, 2021; Uchiyama et al., 2018; Latifah et al., 2024; Íbiş et al., 1992
U (natural/ depleted)	Long-lived; no numeric value given	Air, natural waters, soils, sediments, plants	Accumulates in plant roots and aquatic organisms; retained in humans after ingestion	Kidney, liver, bone, soft tissues	Chen et al., 2021; Bangotra et al., 2021; Xu et al., 2021; Patel et al., 2023; Fallatah et al., 2024
Th (Th-232 etc.)	Long-lived; no numeric value given	Air (dust), natural waters, soils and sediments	Generally low plant uptake; some environmental accumulation	Lung (for inhaled dust); detailed organ distribution not specified	Rump et al., 2023; Patel et al., 2023.

Across these radionuclides, longer physical half-lives like those of Cs-137, Sr-90, uranium and thorium favor long-term environmental persistence, while I-131 is short-lived but highly relevant for acute thyroid doses. Environmental compartment (air vs water vs soil) together with chemical behavior controls bioaccumulation, and characteristic target organs are bone for Sr-90, thyroid for I-131, soft tissues for Cs-137, and kidney–liver–bone–soft tissues for uranium, with thorium posing particular risk to lungs when inhaled as dust.

Radioactive Fallout from Nuclear Weapons Experiments. The beginning of the atomic age marked the outset of nuclear weapons testing, which is responsible for the radioactive contamination of a large number of sites worldwide (Prăvălie, 2014). The United States is one of the important examples of assessing the correlation between the increase in the thyroid cancer incidence rate and the continental-scale radioactive contamination with ^{131}I, a radioactive isotope which was released in large amounts during the nuclear tests carried out in the main test site, Nevada (Prăvălie, 2014).

Data from nuclear weapons tests form the basis for the conclusion that the main part of the radioactivity from high-yield weapons dissipates in the stratosphere, but the small but very significant part that falls out within a few hundred miles of the site of the explosion of weapons fired on the surface constitutes a very real hazard (Libby, 1956). From 1945 to 1980, over 500 weapons tests were conducted in the atmosphere at a number of locations around the world. These tests resulted in the release of substantial quantities of radioactive debris to the environment (Beck & Bennett, 2002).

The impact of weapons fallout will continue to be felt for years to come since a contaminant baseline has been imposed on the ambient radiation environment that will be an important factor in the assessment of past and future releases of radioactive materials into the biosphere (Beck & Bennett, 2002).

Releases of Radioactive Substances into the Environment. When environmental impact and risks associated with radioactive contamination of ecosystems are assessed, the source term and deposition must be linked to ecosystem transfer, biological uptake and effects in exposed organisms. Thus, a well-defined source term is the starting point for transport, dose, impact and risk models (Salbu, 2024).

Several anthropogenic activities produce radioactive materials into the environment. According to reports, exposure to high concentrations of radioactive elements such as potassium (K), uranium (U-238 and U-235), and thorium (Th) poses serious health concerns (Adeola et al., 2022). Although a wide number of industrial processes routinely release radionuclides into the environment, the resulting potential impacts on human health have been largely overlooked in life cycle assessment (LCA) (Paulillo et al., 2023).

Research has also demonstrated that particle characteristics such as elemental composition depend on the emitting source, while characteristics such as size distribution, structure, and oxidation state influencing ecosystem transfer will also depend on the release scenarios. Thus, access to advanced particle characteristic techniques is essential within radioecology (Salbu, 2024). In rivers and potable water, reports show that several parts of Europe and Asia have recorded radionuclide concentrations much higher than the permissible level of 1 Bq/L (Adeola et al., 2022).

The Chernobyl Nuclear Explosion. The explosion on 26 April 1986 at the Chernobyl nuclear power plant and the consequent reactor fire resulted in an unprecedented release of radioactive material from a nuclear reactor and adverse consequences for the public and the environment. Although the accident occurred nearly two decades ago, controversy still surrounds the real impact of the disaster (Higley, 2006).

'In the early morning of April 26, 1986, as the culmination of an almost incredible series of errors that began 24 hours earlier, Unit 4 of the Chernobyl nuclear complex, a so-called RBMK-1000 reactor, suffered the worst accident in the history of commercial nuclear power. There was an uncontrolled nuclear excursion, release of a large amount of energy, possibly comparable to hundreds of pounds of TNT, blowing the top off the reactor. There was no containment, in the traditional American sense, so the roof of the building was blown out, an unprecedented amount of radioactivity was released to the biosphere, and a graphite fire was ignited, which burned for days. The radiation that was released spread through Eastern Europe' (Lewis, 1986).

Radioactive fallout from the accident (directly or indirectly) affected the lives of hundreds of thousands of people in the former Soviet Union, and contamination spread throughout Europe (Smith & Beresford, 2006). The Soviet estimates, in addition to the dispersal of about 3% of the fuel, include the complete release of the noble gas core inventory, 20% of the fission product iodine inventory, 15% of the tellurium inventory, and 10 to 13% of the fission product cesium inventory (Malinauskas, 2023). The iodine and cesium release estimates are not consistent with the noble gas values and are as much as a factor of two lower than some estimates made by experts outside the Soviet Union (Malinauskas, 2023).

The immediate actions involved the fire extinguishing, the cleanup of radioactive residues and the prevention of a new explosion (Naoum & Spyropoulos, 2021). The people who lived nearby were removed. As far as the socio-economic impact for the Soviet Union is concerned, it was quite serious. Moreover, the environmental and human health consequences were also alarming with thyroid cancer being the most studied (Naoum & Spyropoulos, 2021).

The physical effects of the explosion are still sufficiently visible, but the health effects are not at all apparent. Although at least 30 of the workers involved in the clean-up operation died, the experience of Chernobyl illustrates well the difficulties of assessing the health effects of a nuclear accident (Henshaw, 1996).

The Nuclear Accident at the Fukushima Daiichi Nuclear Power Plant. '*On March 11, 2011, the Great East Japan Earthquake struck Japan with a magnitude of 9.0. Within an hour, a tsunami hit the shore. Three reactors at the Fukushima Daiichi Nuclear Power Plant (FDNPP, operated by Tokyo Electric Power Company) lost power. The reactors could not be cooled, and core meltdowns occurred, which resulted in an explosion due to hydrogen being generated at high temperatures. As a result, radioactive materials were released and scattered northwest from the power plant*' (Ito, 2024).

Nuclear accident at the Fukushima Daiichi nuclear power plant (FDNPP), which is located 230 km north of downtown Tokyo, was the most recent tragedy in the nuclear society. The total release of radioactivity was estimated to be 6.3 × 1017 Bq, which is approximately one tenth of the total radioactivity released from the Chernobyl (5.2 × 1018 Bq) (Iwata et al., 2012).

Although some details of the accident are still not well known, the sequences, causes, and consequences of the accidents have been basically clarified by the efforts of several investigation committees in Japan. The fission products released to the environment were estimated by the severe accident analysis code, MELCOR, from inside the reactor core, and also by the atmospheric dispersion simulations code, SPEEDI, by coupling with environmental monitoring data in the reverse estimation method from outside the plant (Sugimoto, 2013).

Conclusions. The comprehensive evaluation of ionizing radiation sources demonstrates that human exposure results from a complex interplay between natural background radiation and anthropogenic activities. Natural sources, including terrestrial radionuclides and cosmic radiation, remain the baseline contributors to global exposure, while medical applications represent the most significant controllable anthropogenic component.

Radionuclides such as Cs-137 and Sr-90 exhibit long-term environmental persistence and significant bioaccumulation potential, leading to prolonged ecological and health implications following nuclear releases. In contrast, short-lived isotopes like I-131 pose acute but temporally limited risks, primarily affecting specific organs such as the thyroid. The study highlights that environmental compartmentalization plays a critical role in radionuclide mobility and exposure pathways, influencing both external and internal dose formation. Despite advances in monitoring and dosimetry, uncertainties persist regarding the biological effects of low-dose radiation, necessitating continued research and refinement of risk models.

Overall, effective radiological protection requires an integrated approach combining environmental monitoring, dose assessment, and regulatory control of anthropogenic sources. Future efforts should prioritize improving the accuracy of exposure assessments and understanding long-term ecological consequences of radioactive contamination.

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